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SUMMARY

Experiments have been conducted to determine the maximum amount of control element lag, and the maximum and minimum control sensitivity that can be tolerated in a single-degree-of-freedom, manually controlled compensatory tracking task. A relatively easy to satisfy error criterion was used to establish the tolerable limit. An automatic controlled element parameter adjustment was used to determine rapidly the limiting value of the parameter. An automatic model-matching method was used to determine the transfer function of the human operator in these tests.

Calculations of the closed-loop system characteristics using the measured pilot transfer function show that the system is being operated with neutral closed-loop stability in the maximum lag configuration, and that the pilot is greatly restricted in his ability to identify, and adjust to, variations in control sensitivity as controlled element lag is increased.

INTRODUCTION

Previous studies, presented in reference 1, have shown that as the lag time constant of the controlled element in a closed-loop, manually controlled tracking task is increased, the system characteristics deteriorated. In particular, the system damping ratio decreased. The maximum controlled element lag studied in reference 1 was that contained in a pure acceleration system $\frac{K_4}{s^2}$ where K_4 is a nondimensional control sensitivity and s is the Laplace operator. Reference 1 also presented data showing that consistent system characteristics could be maintained over a fairly wide range of control sensitivity.

In the present study the maximum amount of controlled element lag that can be tolerated in a single-degree-of-freedom tracking task was determined. The maximum and minimum control sensitivity at several values of controlled element lag was also determined. An easy to satisfy criterion was used to establish the tolerable limit. A given value of average absolute error was arbitrarily chosen for a criterion, and a random disturbance was inserted into the system which had an average absolute value which was smaller than the selected criterion value. The task of the pilot was, therefore, only to avoid divergence in the system. The quantity being investigated, either controlled element lag or control sensitivity, was automatically adjusted as a function of the difference between the absolute average error and the selected criterion. In this manner the maximum lag and maximum and minimum control sensitivity were rapidly determined. This method of parameter adjustment has been previously presented in references 2 and 3. At the same time the transfer function of the human operator was also determined by using the model matching technique presented in reference 1.

SYMBOLS

D	disturbance, volts
K_1,K_2,K_3,K_4	nondimensional computer gains
L	simulated vehicle feedback gain, radians/sec
s	Laplace operator, sec^{-1}
t	time, sec
δ	analog model output, volts
$\delta',\delta'',\delta''',\delta''''$	analog model output at intermediate points, volts
ϵ	analog model input (displayed error), volts
ζ	damping ratio
τ	analog model feedback gain (lag break-point frequency), radians/sec
ω_n	undamped natural frequency, radians/sec

APPARATUS AND TESTS

The task presented to the subjects in these experiments was a single-degree-of-freedom, compensatory tracking task. The pilot's stick output was the input to a simulated controlled element. The output of the controlled element was summed with a random disturbance to form the system error. This system error was presented to the pilot on an oscilloscope as the difference between a moving horizontal line and a fixed reference mark. The pilot's task was to keep the moving line alined with the reference mark as closely as possible at all times. The oscilloscope was 5 inches in diameter and was used with a sensitivity of 4 volts per inch. The pilot exercised control with a pencil-type, spring-loaded, side-arm controller. The maximum electrical output of the controller at full deflection was 25 volts.

A symbolic diagram of the controlled element and the automatic adjustment loop for the controlled element variable is presented in figure 1. In the tests to determine maximum controlled element lag, the transfer function for the controlled element was

$$\frac{\text{Output}}{\text{Input}} = \frac{10L}{s^2(s + L)}$$

The vehicle lag time constant was increased by decreasing the feedback quantity L. The quantity L was also included in the numerator so that the static gain of the controlled element would remain constant at a value of 10. The quantity L was varied automatically as a function of the integral of the difference between a preselected criterion level and the absolute value of the closed-loop system error. The value for the criterion was 2.5 volts. This arrangement of the integrator provided a heavy smoothing of the absolute system error which approximates the average. Thus, if the average of the absolute system error was less than the 2.5-volt criterion, the feedback quantity L was decreased. If the average was equal to 2.5 volts, L would undergo small changes equally divided between increases and decreases about a steady-state value which would represent the maximum controlled element lag time constant that was being sought.

In this paper reference to controlled element lag in general refers to both the order and the amount of feedback included in the transfer function of the controlled element. In the transfer function,

$$\frac{\text{Output}}{\text{Input}} = \frac{K_4}{\left(\frac{1}{A}s + 1\right)\left(\frac{1}{B}s + 1\right)\left(\frac{1}{C}s + 1\right)}$$

when A, B, and C are infinitely large; the terms with the operator s can be considered to be nonexistent and the expression is a zero-order transfer function. When A is considered to have a finite value, the expression is that of a first-order system. As A is decreased, the lag time constant of the system increases. When A becomes zero and B is assumed to have a finite value, the expression becomes that of a second-order system. If B is then decreased, the lag is considered to be increasing further. The difficulty of control for the pilot also increases with this progressive increase in lag.

Previous studies have presented the system characteristics that can be achieved in the manual control of second-order systems. In the present study to determine maximum lag, only third-order systems were considered. For computer compatibility, it was necessary to move the experimental variable for lag from the position of the coefficient of s to the position of the constant term. In order to maintain a constant value of static sensitivity while the lag of the controlled element was being changed, it was necessary to include the variable in the numerator of the transfer function of the controlled element, as was mentioned previously. The initial system presented to the pilot in these tests was

$$\frac{\text{Output}}{\text{Input}} = \frac{10(7)}{s^2(s + 7)}$$

and the numerical value in the denominator, which was the gain of the feedback on the third integrator, was reduced by the automatic adjustment circuit.

The position where the disturbance was inserted in the control loop is also shown in figure 1. This disturbance was obtained from a Gaussian noise generator filtered with two first-order low-pass filters with break frequencies of 1 radian per second. In most tasks the amplitude of the disturbance was adjusted so that the average absolute value of the disturbance was 2.0 volts. Some tasks were conducted with the average absolute value of the disturbance set at 4.0 volts.

In the tests to determine maximum and minimum control sensitivity K_4, three different controlled elements were used with each subject. For pilot J, the controlled elements were $\frac{\text{Output}}{\text{Input}} = \frac{K_4}{s(s + 1)}$, $\frac{K_4}{s^2}$, and $\frac{K_4}{s^2(s + 3)}$. The quantity K_4 was automatically varied. The maximum sensitivity was determined by using the adjustment loop in a positive sense, and the minimum sensitivity by using the adjustment loop in a negative sense. The amount of lag included in the highest order dynamics was set at less than the amount of lag demonstrated as the maximum lag for each subject in the maximum lag tests.

The transfer function of the human operator was determined by using the model matching method described in reference 1. This transfer function has the form

$$\frac{\text{Output}}{\text{Input}} = \frac{\delta}{\epsilon} = \frac{K_1 \tau + K_1 K_2 s}{(s + \tau)^2}$$

The coefficients K_1, K_2, and τ are automatically adjusted to give the best possible match to the human operator. It was demonstrated in reference 1 that the adjustment of the gains in the analog model are not instantaneous, and that the measured gains can be considered accurate only after they have reached a steady value.

It was felt that with the higher order controlled elements, the human operator might be using the second derivative of the input signal as well as the terms present in this model. Therefore, a model of the form

$$\frac{\text{Output}}{\text{Input}} = \frac{K_1\tau^2 + K_1K_2\tau s + K_1K_3s^2}{(s + \tau)^2}$$

was also matched to the human operator. An analog diagram and the partial derivatives of the model coefficients used in the coefficient adjustment loop are presented in the appendix.

Five NASA test pilots and one engineer served as subjects for these tests. Maximum controlled element lag was determined first with an apparently near-optimum control sensitivity. The subject was started with a third-order system with a very short time constant. It was possible for the subject to keep the error well within the criterion. The test then proceeded, the lag of the controlled element being adjusted. After the maximum lag was established, the lag was set at a value somewhat less than the maximum value, and the maximum and minimum control sensitivity was established. At a later session, the maximum and minimum control sensitivities with controlled elements $\frac{K_4}{s(s + 1)}$ and $\frac{K_4}{s^2}$ were determined.

RESULTS AND DISCUSSION

Results of the maximum lag tests are presented in tables I and II and results of the maximum and minimum control sensitivity tests are presented in table III. These tables also include the coefficients of the transfer function of the pilot and the closed-loop system characteristics obtained by using these coefficients. Sample time histories of these tests are shown in figures 2 to 7.

Maximum Lag Tests

The results of the maximum lag tests, presented in table I, show that four of the pilot subjects were able to maintain at least neutrally stable control with controlled elements of approximately

$$\frac{\text{Output}}{\text{Input}} = \frac{15}{s^2(s + 1.5)} .$$

This transfer function can be considered representative of an inertia load being controlled by a proportional control with a first-order response with a time constant of 1/1.5 (or 0.66) second. The closed-loop system characteristics determined by using the measured pilot transfer functions show system damping ratios of approximately zero – ranging from small positive to small negative values in the individual cases. These results give a quantitative confirmation that the pilot is controlling the system so that neutral stability results. The controlled element lag determined in these tasks is therefore a critical case and represents the maximum amount of lag that a human operator can control with a near-optimum control sensitivity. A sample time history of one of these tests is shown in figure 2. The figure illustrates that a consistent value for the maximum lag L is maintained for 2 minutes. The output of the analog model from which the coefficients of the human transfer function were obtained is also shown.

The tests discussed in the previous paragraph were performed with a disturbance inserted in the system which itself satisfied the criterion selected for satisfactory control. This disturbance had an average absolute value of 2.0 volts, and the criterion was 2.5 volts. Additional tests were conducted in which the average absolute value of the disturbance was 4.0 volts. In this latter case it was necessary for the pilot to exercise some regulation of the disturbance to meet the criterion. The feedback L established in these tests is larger (the time constant is shorter in other words) than in the task with the smaller disturbance. The closed-loop system characteristics also show positive values for damping ratio and indicate that the pilot is exercising some regulation. A sample time history is shown in figure 3.

As a guide to the effect of frequency and damping ratio on system performance, as expressed by normalized error, figure 8 is presented. This figure gives the calculated normalized error for a second-order oscillatory system with a 1-second lead time constant in response to a 1 radian per second sinusoidal input as a function of the system characteristic frequency and damping ratio. The figure shows that both an increase in frequency and an increase in damping ratio will result in an improvement in system performance. The figure can also provide a rough check on the validity of the measured transfer function for the human pilot. By locating test points on the figure corresponding to the frequency and damping ratio of the predominant closed-loop system characteristic, a normalized error is indicated. The error thus indicated can be compared with that reached in satisfying the selected error criterion in the tests. An exact agreement cannot be expected because of the simplifying assumptions made in constructing the figure, but good agreement on the difference in error for the tests with the 2-volt average disturbance and the tests with the 4-volt average disturbance would indicate a satisfactory determination of the transfer function for the pilot. The test data plotted on the figure show a positive bias in the indicated error, but good agreement is shown for the difference in error for the two different tests.

An attempt was made to determine whether the human operator uses the second derivative of the displayed error in addition to the error and the first derivative of the error in forming his output function when controlling a high-order system. A model containing the second derivative of the output was programed. The manner in which this model matched a known model of the same form is illustrated in figure 4. It can be seen that the coefficients are determined in 30 seconds. This model was then matched to the taped data obtained in the maximum lag tests. A time history of this match is shown in figure 5 and tabulated results for two of the subjects are shown in table II. A visual inspection of the model matching showed no significant improvement with the complex model. As is shown in table II, a value for the coefficient of the second derivative term K_3 was measured. However, changes in the other coefficients were also recorded. The net effect on the closed-loop characteristics was minor. The predominant system characteristic, the low frequency oscillatory mode of motion with the poor damping, was changed very little. Therefore, it is concluded that including a term for the second derivative of the input in the model for a human operator has not been shown to be warranted.

Minimum and Maximum Control Sensitivity

Experiments were conducted in an attempt to understand what the nature of a maximum or minimum control sensitivity, if such existed, might be. Tests were made with three different sets of dynamics: a low-order easy-to-handle system $\frac{K_4}{s(s + 1)}$; a pure acceleration system $\frac{K_4}{s^2}$; and a high-order difficult-to-handle system of the form $\frac{K_4}{s^2(s + L)}$ where L was varied slightly for each subject. The results for two of the subjects are shown in table III, and two sample time histories are shown in figures 6 and 7. When tests were conducted with the disturbance which itself would satisfy the criterion, the subjects were able to run the minimum sensitivity down to zero with the $\frac{K_4}{s(s + 1)}$ system. Therefore, those tasks were repeated with the disturbance which had a higher average value than the criterion.

The closed-loop system characteristics obtained by using a constant-coefficient linear model for the pilot with the minimum and maximum vehicle control sensitivity show no consistent reason for the existence of a maximum value. In reference 1 it is shown that with the dynamics $\frac{10}{s(s + 1)}$, which has a near optimum value for control sensitivity, the closed-loop system characteristics are a natural frequency of about 3 radians per second and a damping ratio of 0.3. With $\frac{10}{s^2}$ dynamics, the average frequency was 2.5 radians per second and the damping ratio 0.2. The system characteristic obtained in the present study with the maximum control sensitivities with these dynamics shows either a lower frequency than that obtained with the optimum sensitivity, or a higher frequency in combination with a low damping ratio. A low system frequency was always obtained with the minimum sensitivity. It should be pointed out that with this minimum control sensitivity, the pilot always moved the control stick full deflection from stop to stop; this restriction may explain the low system frequencies.

One consistent result was obtained in all tests. The spread in control sensitivity K_4 with which the given error criteria could be met varied as a function of the lag in the controlled element. The largest spread was obtained with the smallest control element lag, and this spread was more restricted with increasing lag. The measured pilot transfer function shows that the reason for this restriction is that there is little or no adaptation in the pilot's static gain $\frac{K_1}{\tau}$ with the $\frac{K_4}{s^2(s + 3)}$ dynamics. The largest variations measured were exhibited by pilot J and are shown on table III. This result indicates that there is a large reduction in the pilots' ability to identify, and adjust to, variations in control sensitivity with increasing lag.

CONCLUSIONS

Tests have shown that there exist controlled element dynamics with which a human operator, using his best control effort, can maintain only neutrally stable closed-loop system characteristics. The transfer function for the critical controlled element is approximately

$$\frac{\text{Output}}{\text{Input}} = \frac{K_4}{s^2(s + 1.5)}$$

where K_4 is a nondimensional control sensitivity and s is the Laplace operator.

It has been further shown that although it is possible to meet a given error criterion with a very wide variation in control sensitivity K_4 with the controlled element

$$\frac{\text{Output}}{\text{Input}} = \frac{K_4}{s(s + 1)}$$

the range in K_4 with which the same error criterion can be met with the controlled element

$$\frac{\text{Output}}{\text{Input}} = \frac{K_4}{s^2(s + 3)}$$

is very restricted. Measurements of the human-operator transfer function show that although the pilot identifies changes in controlled element control sensitivity and adjusts his own static sensitivity when the controlled element lag is low, the pilot's ability to adapt to changes in sensitivity is greatly restricted as controlled element lag is increased.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 26, 1965.

APPENDIX

PILOT MODEL AND PARTIAL DERIVATIVES

The pilot model which contained the second derivative of the input was of the form

$$\frac{\text{Output}}{\text{Input}} = \frac{\delta}{\epsilon} = \frac{K_1\tau^2 + K_1K_2\tau s + K_1K_3s^2}{(s + \tau)^2}$$

An analog diagram of this model is shown in figure 9.

The approximate partial derivatives of the output with respect to the various coefficients, which were used in the coefficient adjustment loops, are:

$$\frac{\partial\delta}{\partial K_1} = \frac{\tau^2 + K_2\tau s + K_3s^2}{(\tau + s)^2}\epsilon$$

$$\frac{\partial\delta}{\partial\tau} = \frac{2\delta' + K_2\delta'' - 2\delta}{\tau + s}$$

$$\frac{\partial\delta}{\partial K_2} = -\delta'''$$

$$\frac{\partial\delta}{\partial K_3} = -\delta''''$$

where the following expressions have been used in making substitutions:

$$\delta' = \frac{\epsilon K_1\tau}{s + \tau}$$

$$\delta'' = \frac{\epsilon K_1 s}{s + \tau}$$

$$\delta''' = \frac{-\epsilon K_1\tau s}{(s + \tau)^2}$$

$$\delta'''' = \frac{-\epsilon K_1 s^2}{(s + \tau)^2}$$

REFERENCES

1. Adams, James J.; and Bergeron, Hugh P.: Measured Variation in the Transfer Function of a Human Pilot in Single-Axis Tasks. NASA TN D-1952, 1963.

2. Ziegler, P. N.; Birmingham, H. P.; and Chernikoff, R.: An Equalization Teaching Machine. NRL Rept. 5855, U.S. Naval Res. Lab., Nov. 20, 1962. (Available as ASTIA Doc. AD 291627.)

3. Hudson, E. M.: An Adaptive Tracking Simulator. Paper presented at First International Congress on Human Factors in Electronics (Long Beach, Calif.), May 3-4, 1962.

TABLE I.- SUMMARY OF DATA OBTAINED IN TESTS TO DETERMINE MAXIMUM LAG

[Controlled element transfer function, $\frac{10L}{s^2(s + L)}$; pilot model, $\frac{\delta}{\epsilon} = \frac{K_1\tau + K_1K_2s}{(s + \tau)^2}$; criterion voltage, 2.5]

Pilot	Measured parameters				Closed-loop characteristics		
					Oscillatory		Real roots
	L (**)	K_1	τ, rad/sec	K_2	ω_n, rad/sec	ζ	
Average absolute value of disturbance, 2.0 volts							
B	1.0	6	21	20	1.63 21.2	-0.08 .99	-1.0
D	2.0	8	17	22	3.18 18.0	-.02 .98	-.83
J	1.5	12	28	30	2.50 28.4	.003 .99	-1.0
K	1.5	9	30	14	1.59 30.1	.13 .99	-1.77
L	4.0	7	21	12	2.16 21.6	.12 .99	-2.69
*H	2.5	10	23	34	3.69 24.0	.05 .98	-.73
Average absolute value of disturbance, 4.0 volts							
B	4.5	8	18	12	2.92 19.2	0.25 .98	-1.38
D	4.5	8	18	18	3.73 19.6	.14 .97	-1.21
J	5.0	10	30	20	2.40 30.6	.29 .99	-2.76
K	5.5	10	29	15	2.03	.24	-25.4, -32.4, -4.68
L	3.5	12	27	14	2.42 27.5	.067 .99	-2.56
*H	3.0	15	31	40	4.06 31.9	.115 .99	-.85

*Engineer.

**Minimum value determined with each subject.

TABLE II.- SUMMARY OF DATA OBTAINED IN TESTS TO DETERMINE MAXIMUM LAG

[Controlled element transfer function, $\frac{10L}{s^2(s + L)}$; pilot model, $\frac{\delta}{\epsilon} = \frac{K_1\tau^2 + K_1K_2\tau s + K_1K_3s^2}{(s + \tau)^2}$; criterion voltage, 2.5; average absolute value of disturbance, 2.0 volts]

Pilot	Measured parameters					Closed-loop characteristics		
						Oscillatory		Real roots
	L (*)	K_1	τ, rad/sec	K_2	K_3	ω_n, rad/sec	ζ	
B	1.0	0.45	4.0	2.5	6	1.50 2.29	-0.13 .73	-6.06
J	1.5	.60	5.0	4.8	9.0	2.63 2.02	.053 .80	-7.98

*Minimum value determined with each subject.

TABLE III.- SUMMARY OF DATA OBTAINED IN TESTS TO DETERMINE MAXIMUM AND MINIMUM CONTROL SENSITIVITY

$$\left[\text{Pilot model, } \frac{\delta}{\epsilon} = \frac{K_1\tau + K_1K_2s}{(s + \tau)^2}\text{; criterion voltage, 2.5}\right]$$

(a) Pilot J

Controlled element	Test	Measured parameters: K_4	K_1	τ, rad/sec	K_2	Closed-loop characteristics, Oscillatory: ω_n, rad/sec	ζ	Real roots
Average absolute value of disturbance, 2.0 volts								
$\frac{K_4}{s^2(s + 3)}$	Maximum	180	6	32	13	3.52 32.6	0.06 .99	-2.62
	Minimum	25	15	28	25	3.08 28.6	.125 .99	-1.35
$\frac{K_4}{s^2}$	Maximum	200	0.13	7.5	15	5.31	.15	-0.54, -12.9
	Minimum	.40	30	8.5	6.5	1.34	.32	-5.13, -11.0
$\frac{K_4}{s(s + 1)}$	Maximum	600	0.075	16.5	3.8	1.68	0.40	-19.2, -13.5
	Minimum	0	-----	---	---	----	----	-----------
Average absolute value of disturbance, 4.0 volts								
$\frac{K_4}{s(s + 1)}$	Minimum	0.15	12.5	8.0	1.5			-0.40, -0.58, -7.64, -8.37

(b) Pilot L

Controlled element	Test	Measured parameters: K_4	K_1	τ, rad/sec	K_2	Closed-loop characteristics, Oscillatory: ω_n, rad/sec	ζ	Real roots
Average absolute value of disturbance, 2.0 volts								
$\frac{K_4}{s^2(s + 5)}$	Maximum	50	6	20	14	2.30 20.9	0.25 .98	-2.60
	Minimum	35	6	21	14	1.62	.20	-3.74, -15.4, -29.2
$\frac{K_4}{s^2}$	Maximum	650	0.30	18	4.5	3.70	0.21	-10.8, -23.6
	Minimum	.15	12.5	5.0	5.0	.65	.18	-6.13, -3.63
$\frac{K_4}{s(s + 1)}$	Maximum	1150	0.075	7.5	6.0	6.10	0.091	-1.28, -13.6
	Minimum	0	-----	---	---	----	----	-----------
Average absolute value of disturbance, 4.0 volts								
$\frac{K_4}{s(s + 1)}$	Minimum	0.10	12.5	4.0	3.0	0.65	0.85	-3.09, -4.8

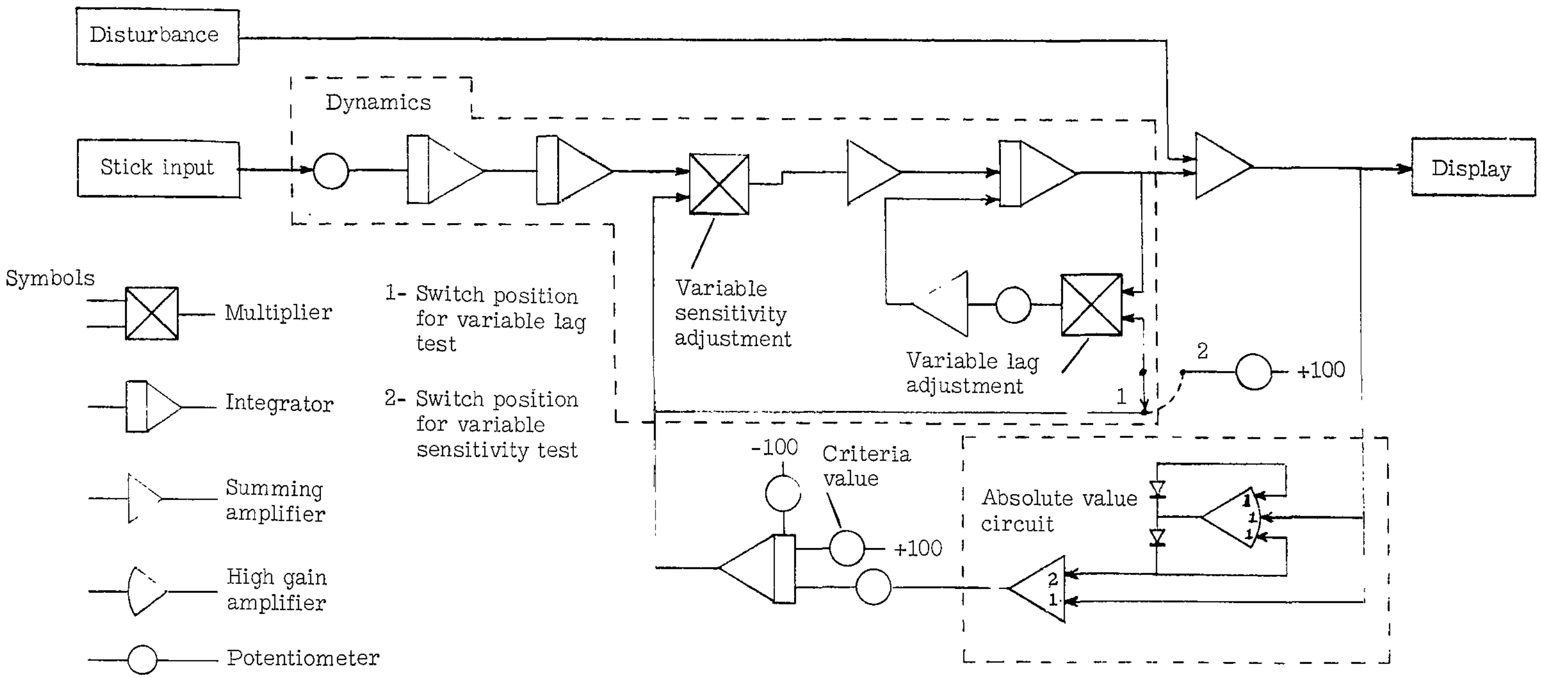

Figure 1.- Computer diagram of control system showing automatic gain and lag adjustment circuit of the dynamics.

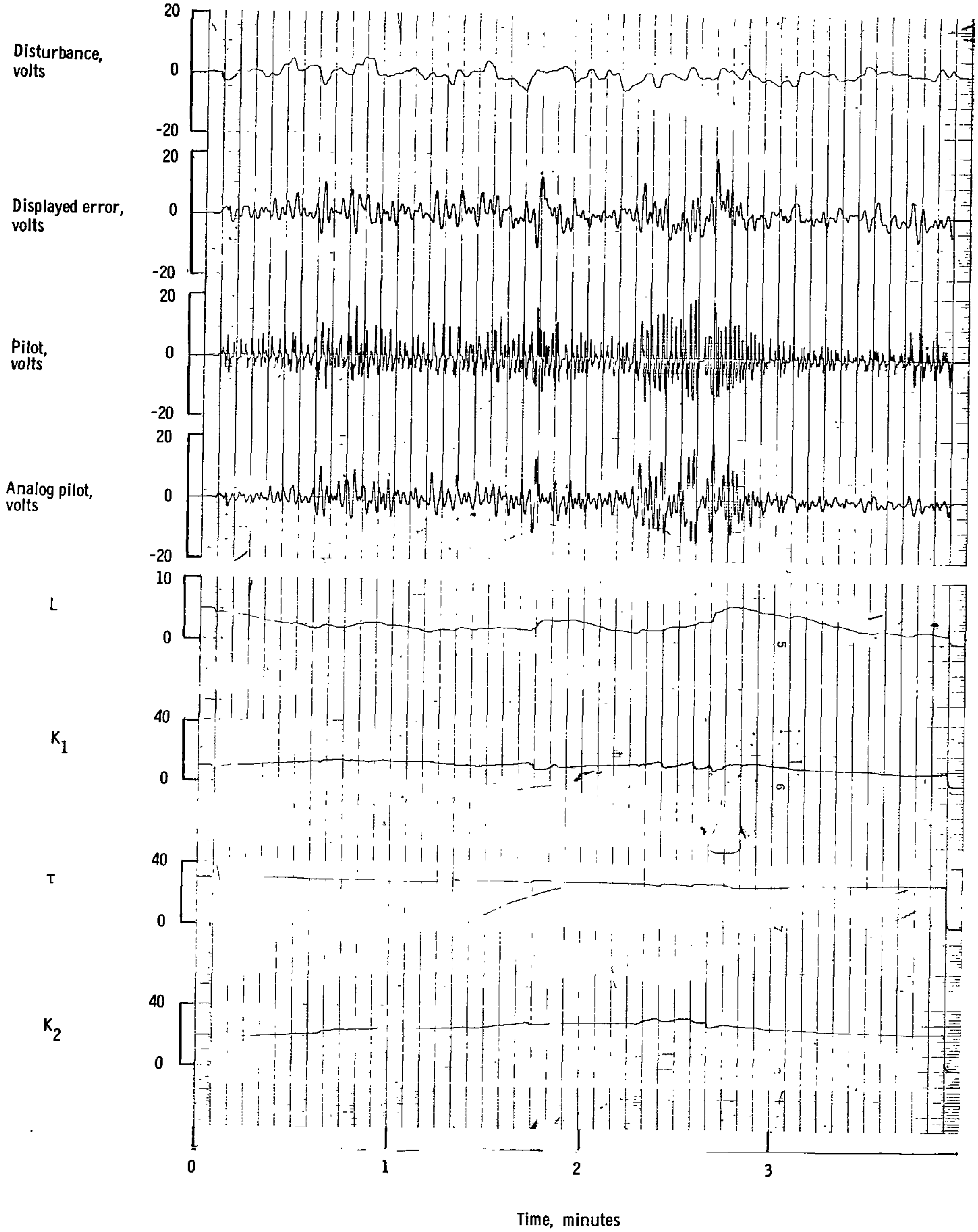

Figure 2.- Determination of maximum controlled element lag when disturbance has a 2-volt average value for pilot J.

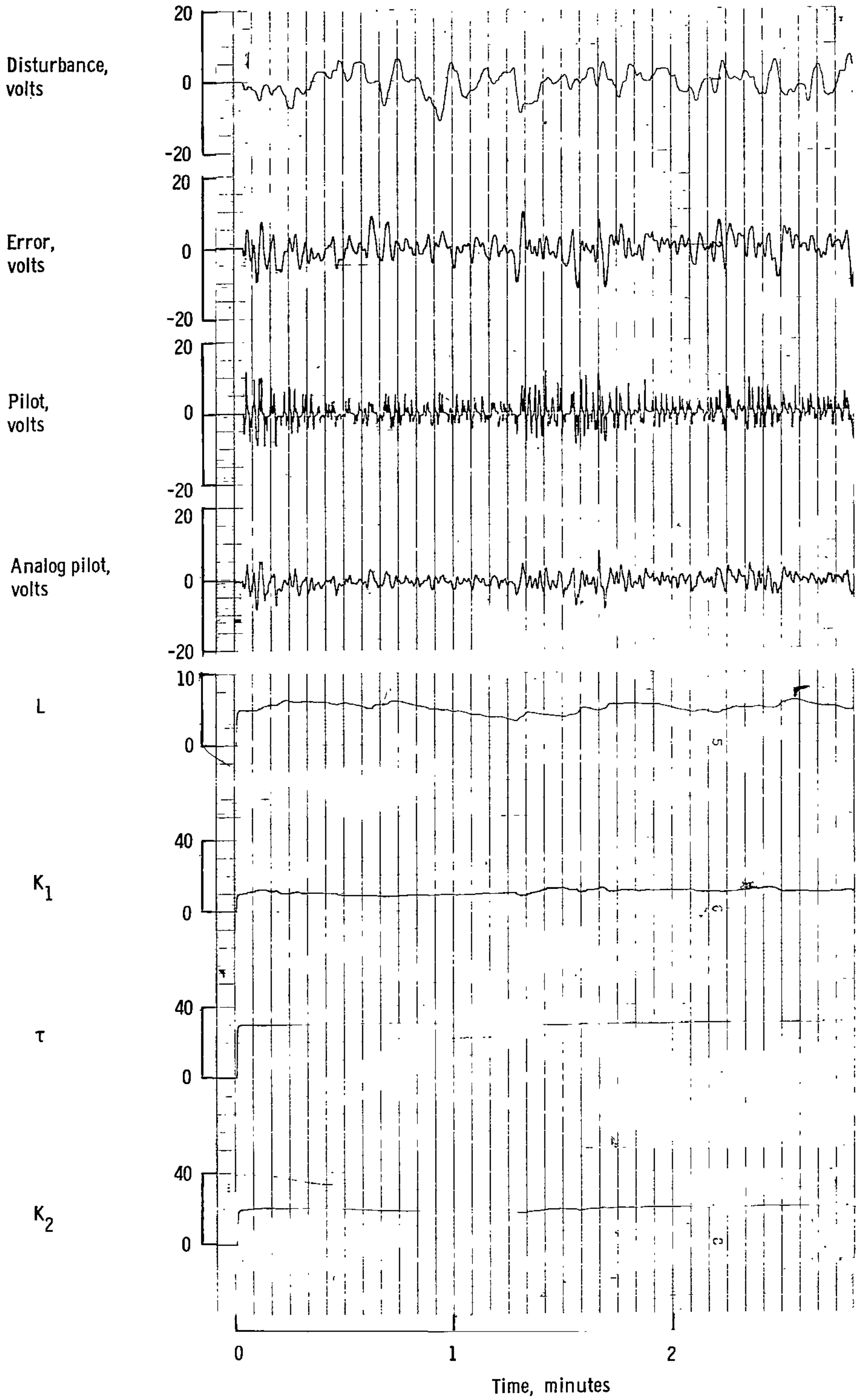

Figure 3.- Determination of maximum controlled element lag when disturbance has a 4-volt average value for pilot J.

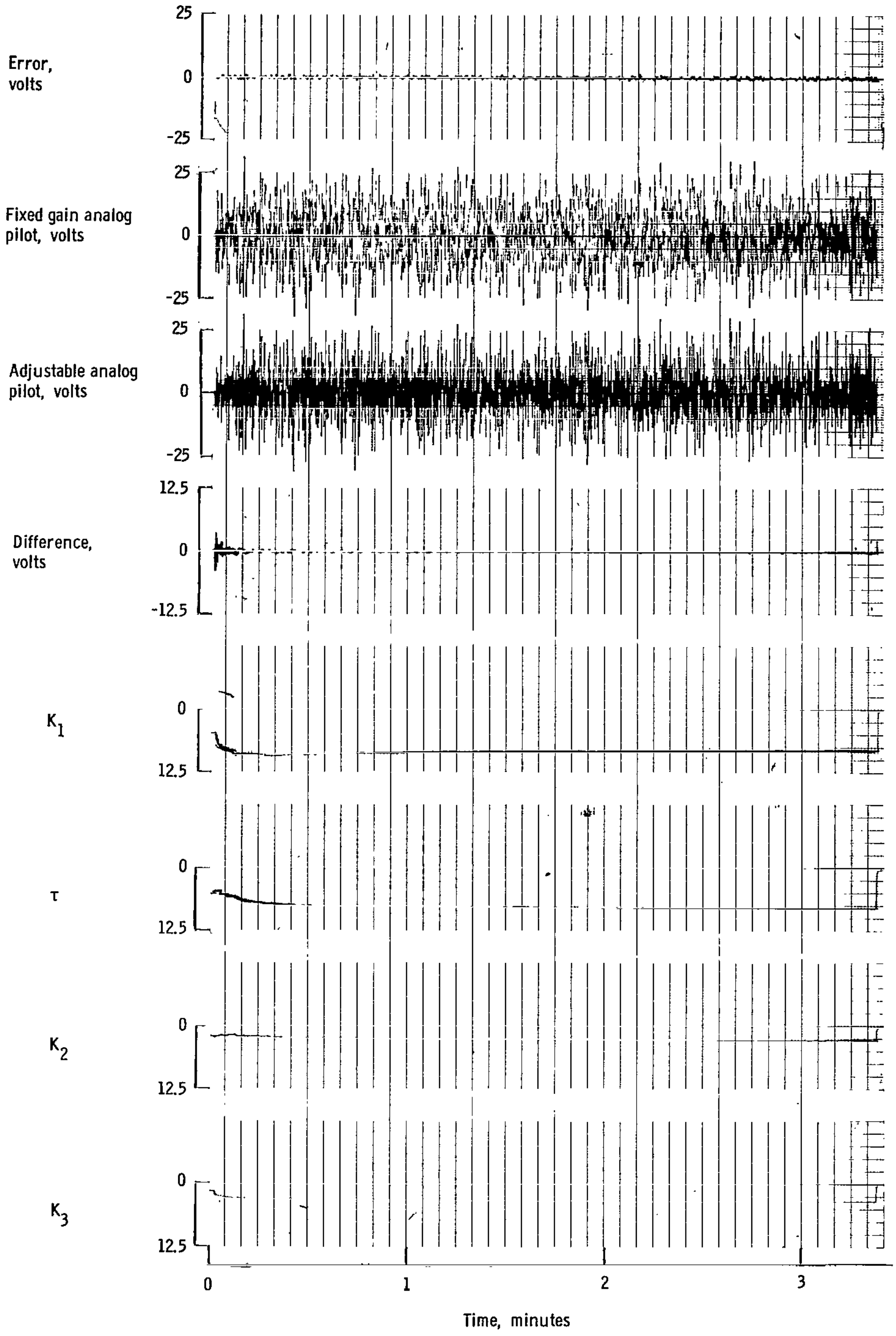

Figure 4.- Match of $\dfrac{K_1\tau^2 + K_1K_2\tau s + K_1K_3s^2}{(s+\tau)^2}$ model to known system which has gains $K_1 = 8$, $\tau = 8$, $K_2 = 3$, $K_3 = 4$.

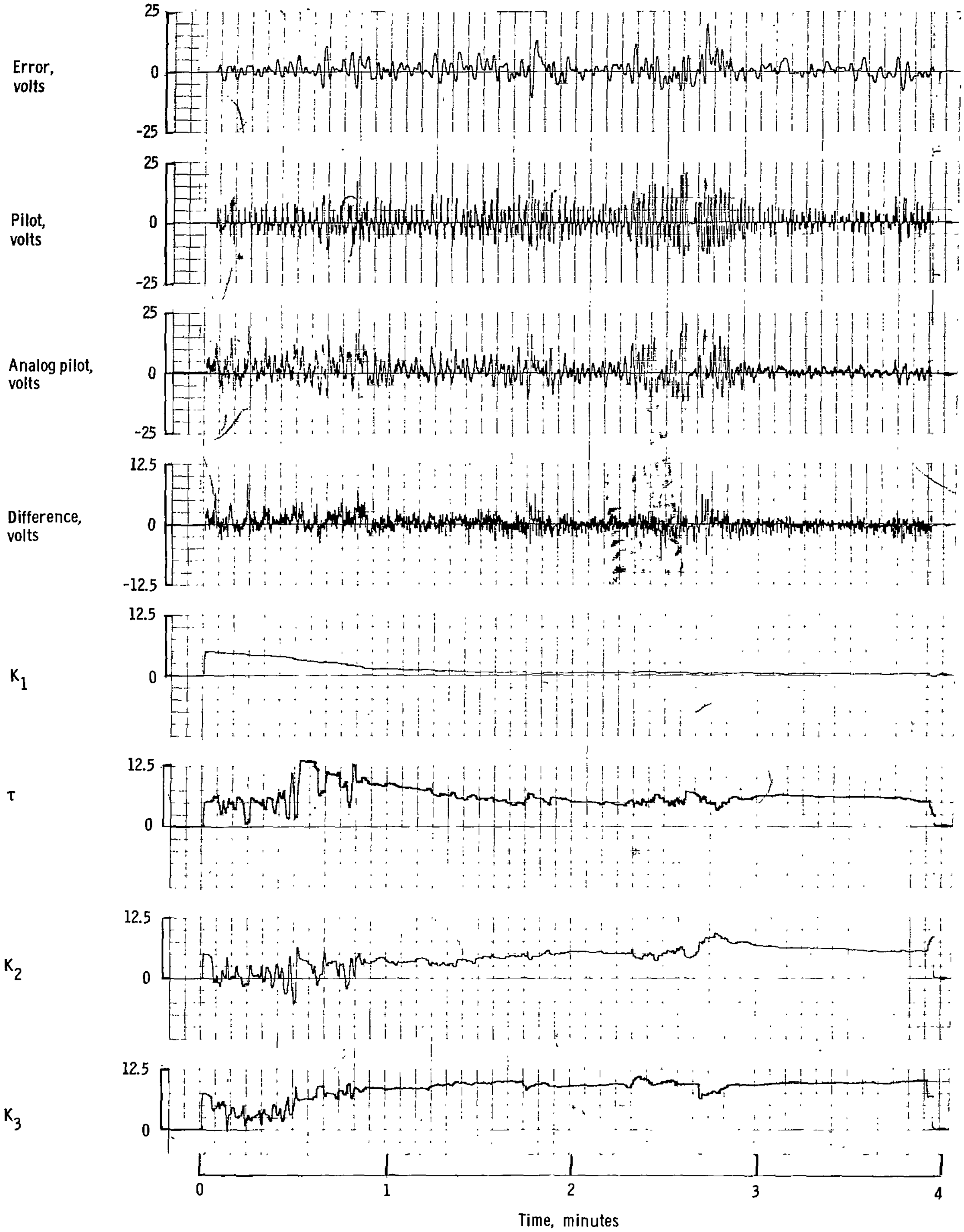

Figure 5.- Repeated analysis of maximum lag test using analog model of the form $\frac{K_1\tau^2 + K_1K_2\tau s + K_1K_3s^2}{(s + \tau)^2}$.

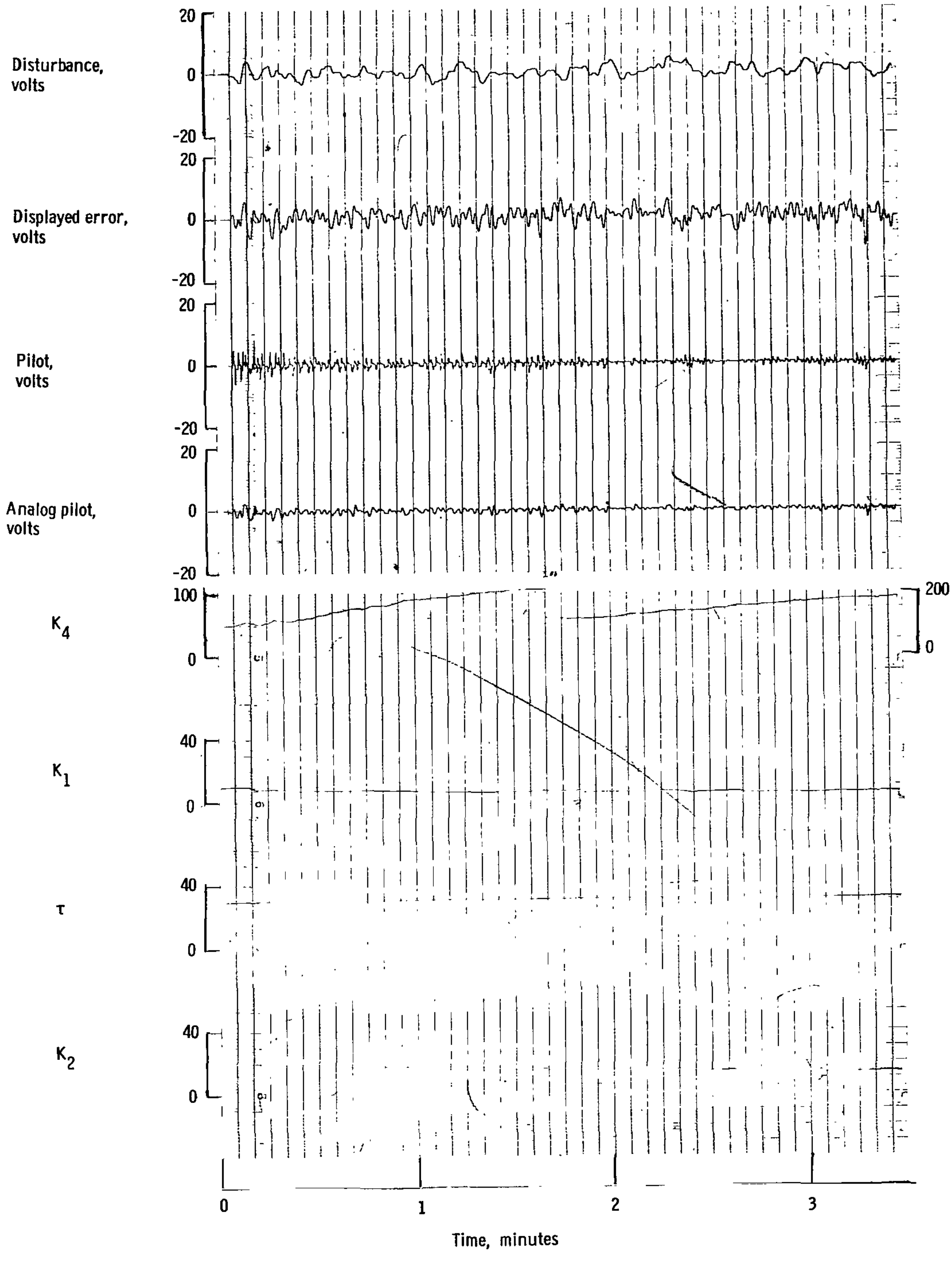

Figure 6.- Time history of maximum sensitivity with $\frac{K_4}{s^2(s+3)}$ dynamics for pilot J.

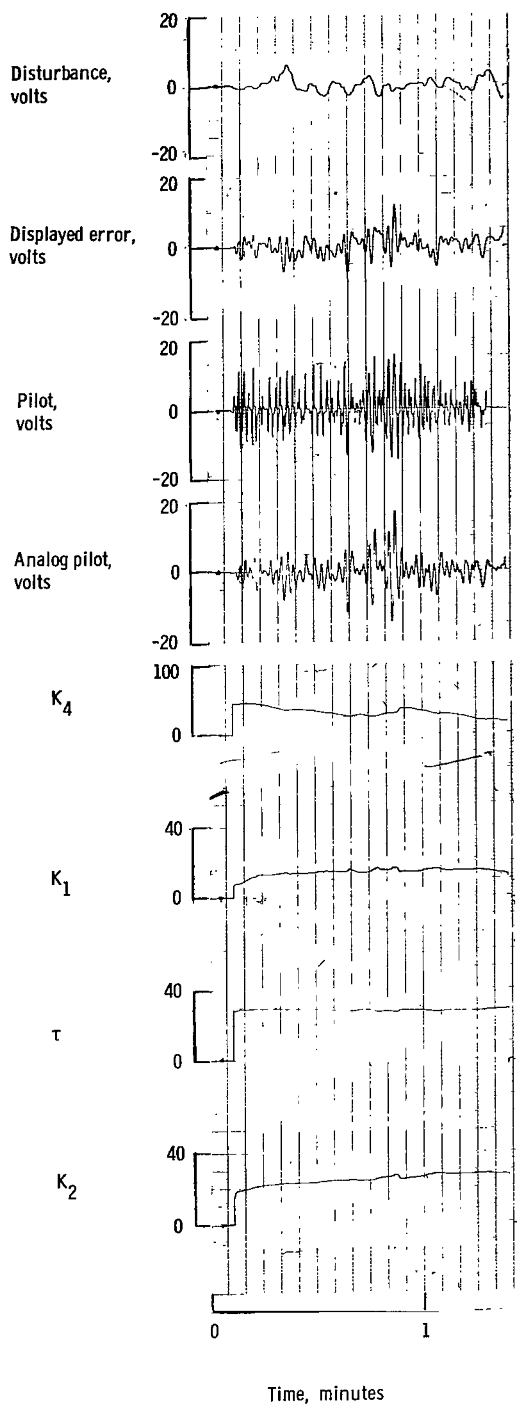

Figure 7.- Time history of minimum sensitivity run with $\frac{K_4}{s^2(s + 3)}$ dynamics for pilot J.

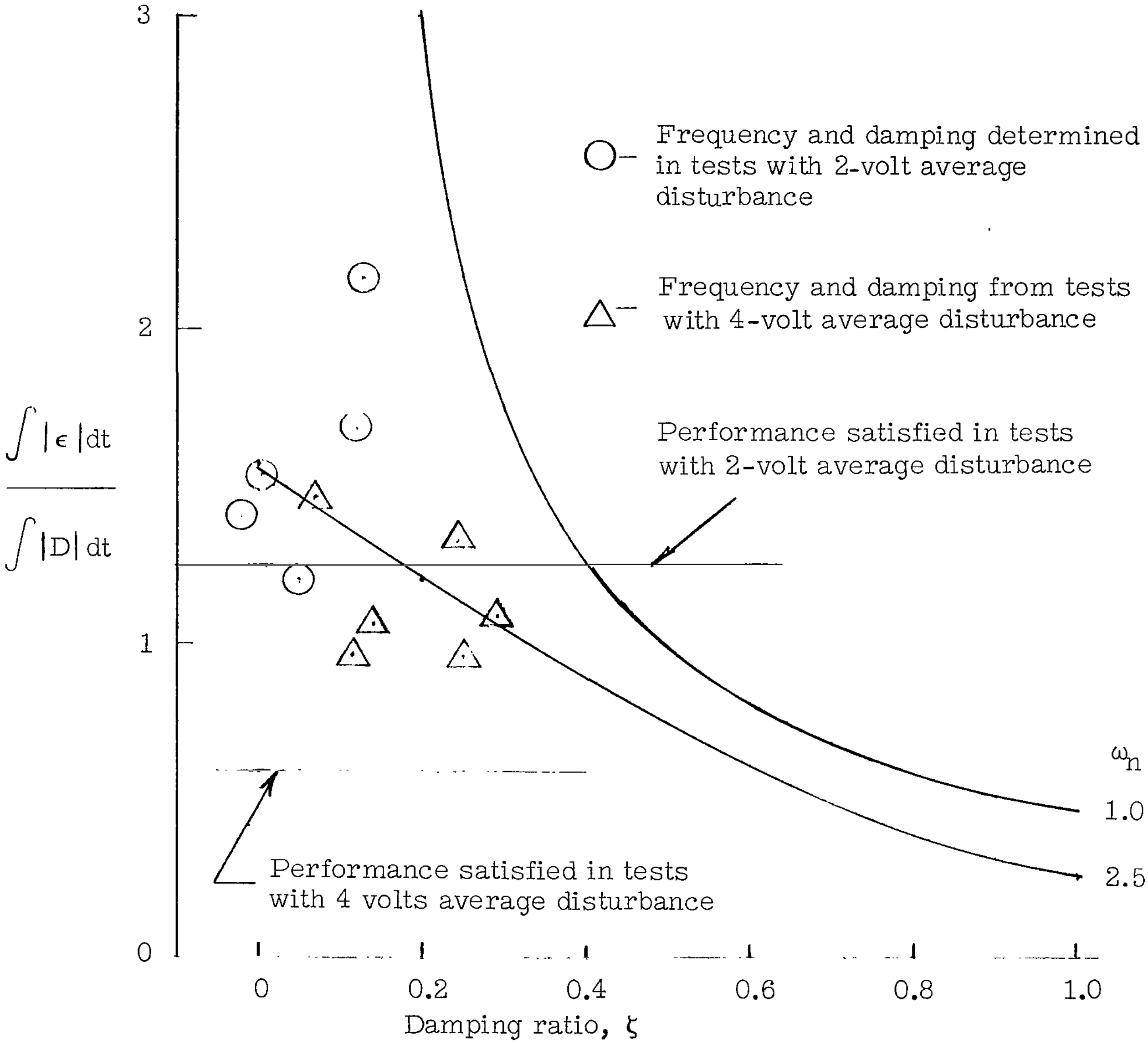

Figure 8.- Calculated normalized error as a function of system frequency and damping ratio for a 1-radian-per-second sinusoidal disturbance.

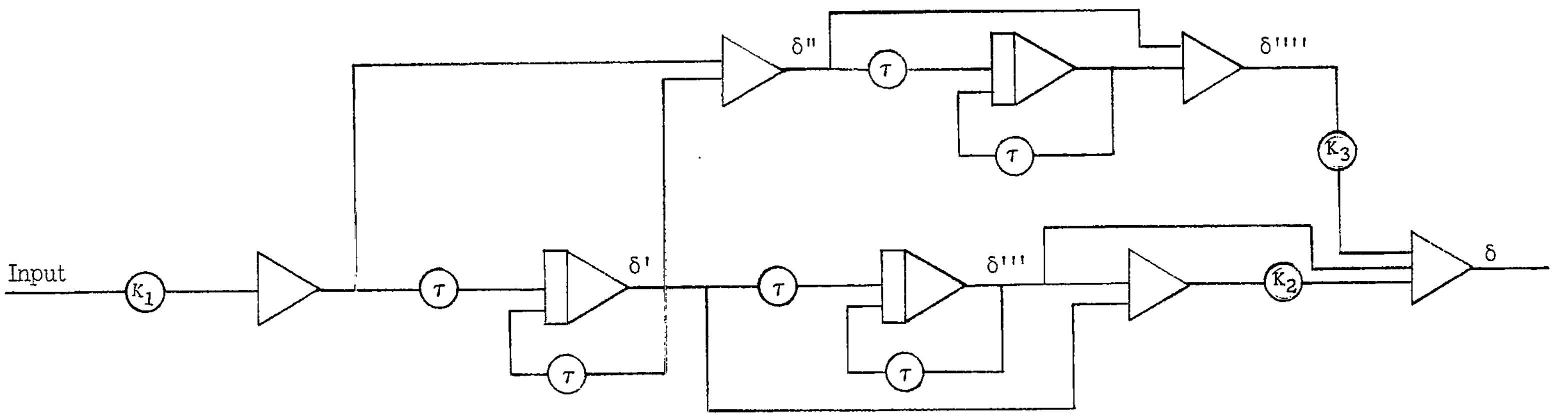

Figure 9.- Computer diagram of model $\dfrac{K_1\tau^2 + K_1K_2\tau s + K_1K_3s^2}{(s + \tau)^2}$.

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